DYNAMIC PROPERTY OF THE FROZEN-LAYER AND ITS EFFECTS ON WARPAGE IN INJECTION MOLDED PARTS

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Abstract

The formation of the frozen-layer, which covers skin layer and orientation layer, will affect the shrinkage at mold during cooling cycle and post-shrinkage of the part after ejecting out from the mold on both flow and transverse directions. However, its physical mechanism and effects on the warpage are still not fully understood. In this study, the dynamic properties of the frozen-layer are investigated numerically. Through the study of dynamic behavior of the frozen-layer formation at the whole molding process, including shear rate variation, relaxation time change, and other properties, its physical mechanism and its effects on shrinkage and warpage can be observed.

Introduction

In the plastic injection molded product development and fabrication, warpage is one of the crucial problems to dominant the quality of product. However, the major effects on the warpage are still not fully under control. In general, the integration of product design, mold design, material selection, and various operation conditions has been regarded as the major factor. However, the physical mechanism for wapage is still too complicated to manage. In the recent years, many researchers have paid their attention to the behavior of frozen-layer [1-4]. The flow characteristics and internal structures are complex and they will affect the mechanical properties significantly. Also, for a given material, the frozen-layer development depends on the local thermal conditions, which may change during the processing. Most of their results were focused on the internal structures of the layers based on the final injected product, and observed the features by optical equipment, such as polarized light microscopy. But what is the dynamic property of the frozen-layer? how is it growing? and how is it related to warpage dynamically? Those in-situ characteristics are not fully understood.

In this study, we have tried to visualize the dynamic growing behavior of the frozen-layer in both perpendicular direction and flow direction numerically. Through the uniform and non-uniform moldbase temperature settings, the frozen-layer will be generated from the top and bottom halves. Some local thermal environments and forming procedures will result in unbalanced frozen-layer. The formation of frozen-layer will contribute to the residual stress generation and then to affect the warpage of injection parts.

Theory Approach and Assumption

The major analysis procedures for injection molding processes include filling, package, cooling, and warpage. In filling/packing stages, the polymer melt is assumed to behave as Generalized Newtonian Fluid (GNF). Hence the non-isothermal 3D flow motion can be mathematically described by the followings:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}\mathbf{u} - \boldsymbol{\sigma}) = \rho \mathbf{g} \tag{2}$$

$$\boldsymbol{\sigma} = -p\mathbf{I} + \eta\left(\nabla \mathbf{u} + \nabla \mathbf{u}^T\right) \tag{3}$$

$$\rho C_P \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T\right) = \nabla(\mathbf{k}\nabla T) + \eta \dot{\gamma}^2 \tag{4}$$

where u is the velocity vector, T is the temperature, t is the time, p is the pressure, σ is the total stress tensor, ρ is the density, η is the viscosity, is k the thermal conductivity, Cp is the specific heat, and $\dot{\gamma}$ is the shear rate.

The FVM (finite volume method), due to its robustness and efficiency, is employed in this study to solve the transient flow field in complex three-dimensional geometries. During the molding cooling stage, a three-dimensional, cyclic, transient heat conduction problem with convective boundary conditions on the cooling channel and mold base surfaces is involved [5, 6]. In this work, the Modified-Cross model with Arrhenius temperature dependence is employed to describe the viscosity of polymer melt:

$$\eta(T, \dot{\gamma}) = \frac{\eta_o(T)}{1 + \left(\eta_o \dot{\gamma} / \tau^*\right)^{1-n}} \tag{5}$$

with

$$\eta_o(T) = BExp\left(\frac{T_b}{T}\right) \tag{6}$$

where n is the power law index, η_o is the zero shear viscosity, and τ^* is the parameter that describes the transition region between zero shear rate and the power law region of the viscosity curve.

After the part is ejected from the mold, a free shrinkage happens due to the temperature and pressure difference. The mechanical properties are assumed as elastic for warpage analysis. The equilibrium equation with σ representing the stress and **F** representing the body force and the thermal load as follows,

$$\nabla\sigma + F = 0 \tag{7}$$

and the relation between stress and strain,

$$\sigma = C(\varepsilon - \varepsilon^{0} - \alpha\Delta T) \tag{8}$$

$$\varepsilon = \frac{1}{2}(\nabla\mathbf{u} + \nabla\mathbf{u}^{T}) \tag{9}$$

where σ is the stress tensor, **C** is a 4th tensor related to the material mechanical properties, ε is the strain tensor, α is CLET tensor and **u** is the displace tensor.

Investigation Procedures

To get better understanding of the dynamic property of frozen-layer and its effect on the warpage, we have applied Moldex3D R9.0 to perform numerical analysis. The geometrical model includes moldbase and cooling channels are shown in Fig. 1. The dimension of injection part is 60 mm X 30 mm X 2 mm. We have setup the measuring nodes from ID 1 to ID9 to catch the dynamic properties as shown in Fig. 2. For each measuring node, there are 20 layers in thickness direction. The testing material is BASF PP Novolen 1102H. One of the process condition settings is listed in Table 1. In this case, the filling is 1 sec; packing is 5 sec; cooling is 20 sec; melt temperature is 210^{o}C; and mold temperature is 35^{o}C.

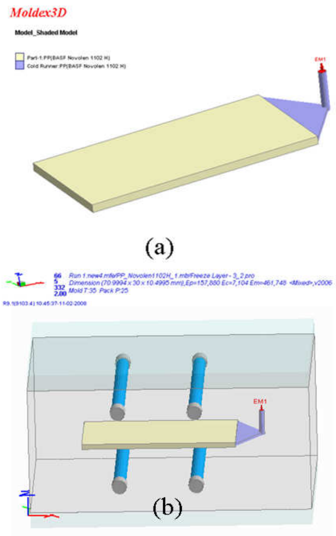


Fig. 1. (a) The geometry model for the part with dimension of 60 mm X 30 mm X 2 mm, (b) the moldbase and cooling channel layout.

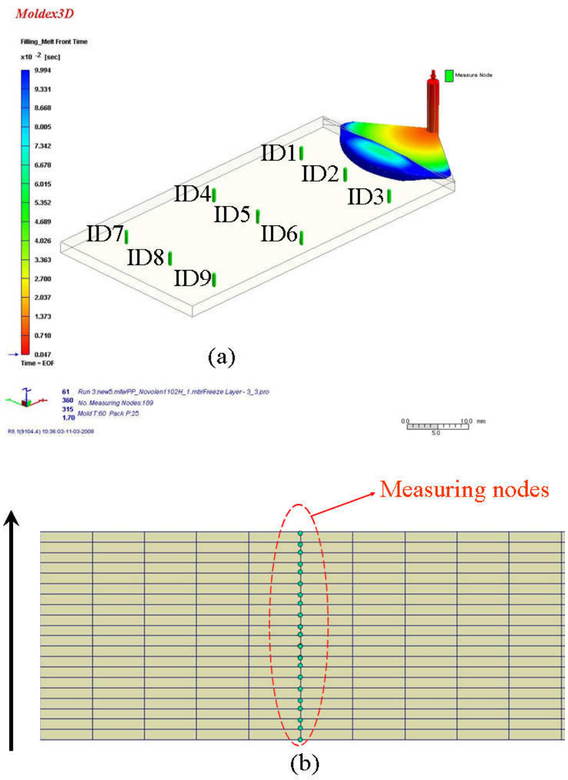


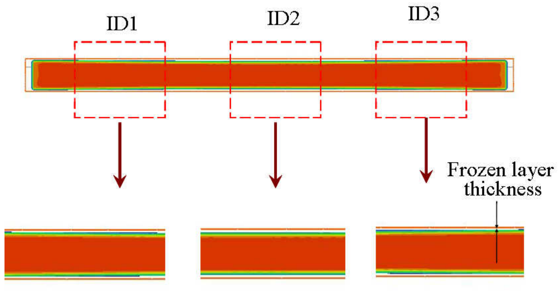
Fig. 2. The measuring nodes setting in the system: (a) specified for ID1 to ID9; (b) the mesh is divided as 20 layers in thickness direction, and the locations of the measuring nodes.

Table 1. One of the process condition settings.

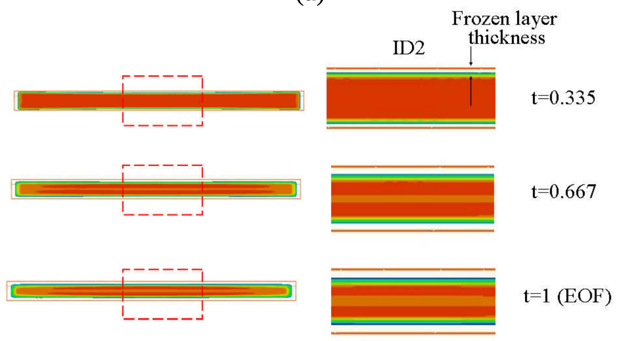
[Filling]	
Filling time (sec)	1
Melt Temperature (oC)	210
Mold Temperature (oC)	35
Maximum injection pressure (MPa)	100
Injection volume (cm^3)	3.78376
[Packing]	
Packing Time (sec)	5
Maximum packing pressure (MPa)	100
[Cooling]	
Cooling Time (sec)	20
Mold-Open Time (sec)	5
Eject Temperature (oC)	145
Air Temperature (oC)	25
[Miscellaneous]	
Cycle time (sec)	31
Mesh file	new4.mfe
Material file	PP_Novolen1102H_1.mtr

Results and Discussions

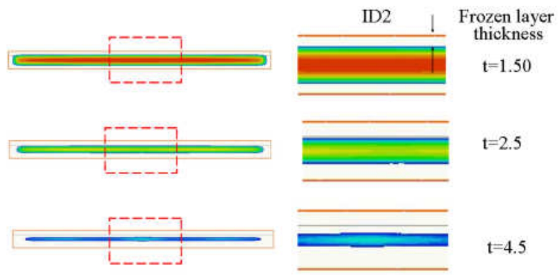
Fig. 3(a) shows the frozen-layer behavior in perpendicular direction with uniform mold temperature of 35 ^{o}C at t = 0.335 sec (the cross section covers ID1 to ID3). The frozen-layer is defined from mold surface to the higher temperature melt inside as shown in white color region. Fig. 3(b) and (c) illustrate the frozen-layer growing behavior from t = 0.335 to 4.55 sec at ID2 region. Obviously, the hot melt is continuously cooled down, and the frozen-layer is developed gradually.



(a)



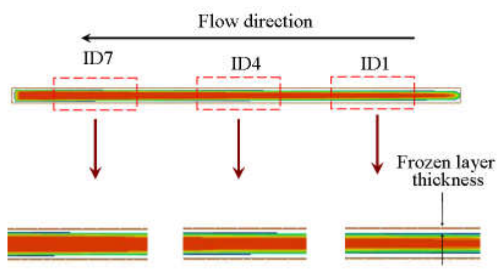
(b)



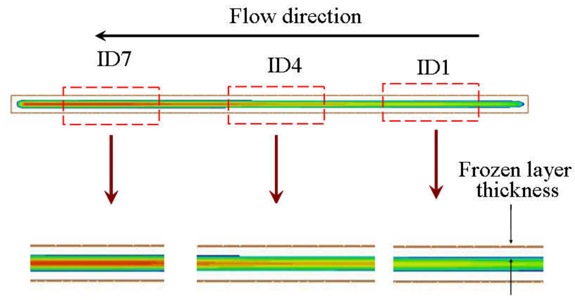
(c)

Fig. 3. The frozen-layer behavior in the perpendicular direction: (a) at t = 0.335 sec; (b) in ID2 region, t = 0.335 to 1 sec (EOF); (c) in ID2 region, t = 1.5 to 4.5 sec.

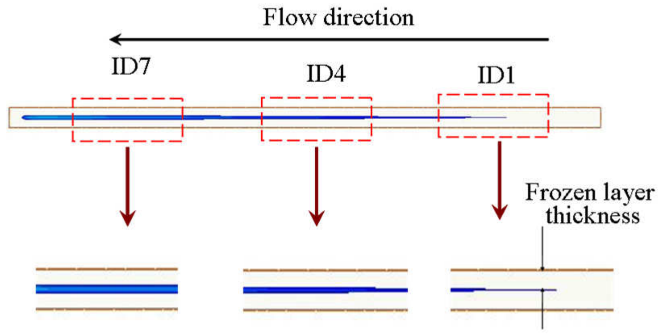
Fig. 4(a) expresses the frozen-layer behavior in flow direction with uniform mold temperature of 35 °C at t = 1.24 sec (the cross section covers ID1 to ID4 and to ID7). Since ID7 is the final region for melts to fill, the melt temperature is higher than those of ID1 and ID4 regions. Fig. 4(b) and (c) further demonstrate the frozen-layer growing behavior from t = 1.24 to 4.47 sec. Unlike Fig. 3(b) and (c), due to the filling is performed sequentially in flow direction, the ID1 region will be frozen faster than ID4 and ID7 regions from the beginning to the end.



(a)



(b)



(c)

Fig. 4. The frozen-layer growing in the flow direction: (a) at t = 1.24 sec; (b) t = 2.96 sec; (c) t = 4.47 sec.

Moreover, to catch the dynamic properties of the frozen-layer, we have focused on both top layer (defined as Z1) and bottom layer (defined as Z2) as shown in Fig. 5. It shows that both Z1 and Z2 have the same trend in ID2 region with uniform mold temperature of 35 °C. For other regions, they show the same feature. Fig. 6 illustrates the dynamic variation of frozen-layer in different regions in the perpendicular direction. Here, because ID1 and ID3 are symmetry, their frozen-layer growing feature is the same. In addition, during the early stage, hot melt in ID2 region contacted mold surface earlier than ID1 and ID3 regions, the frozen-layer of ID2 is larger than those of ID1 and ID3. However, when it goes to the final stage of filling, the flow rate in ID2 is higher than that in ID1. The growing of the frozen-layer in ID2 is then slower down. That is the reason for the existence of intersection point in Fig. 6. In addition, during the filling stage, Fig. 7 illustrates the frozen-layer developing in the flow direction with uniform mold temperature of 35 °C. Since ID1 region is the first one to be filled and contacted cold wall, the frozen-layer in this region is larger than those in ID4 and ID7. In all regions in the flow direction, it shows the similar tendency of frozen-layer growing.

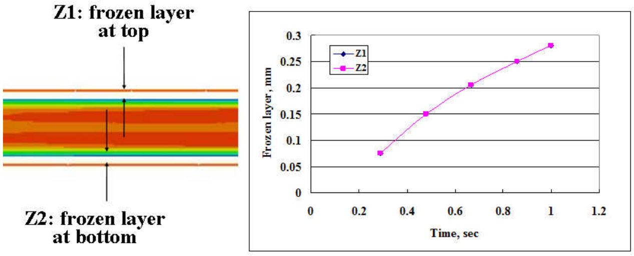


Fig. 5. The frozen layer in ID2 region, where Z1 is the frozen-layer at top, and Z2 is the frozen-layer at bottom.

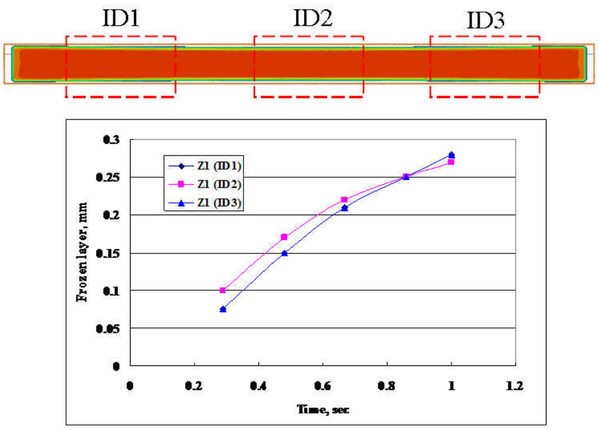


Fig. 6. The dynamic variation of the frozen-layer with uniform mold temperature of 35°C in the perpendicular direction during the filling stage.

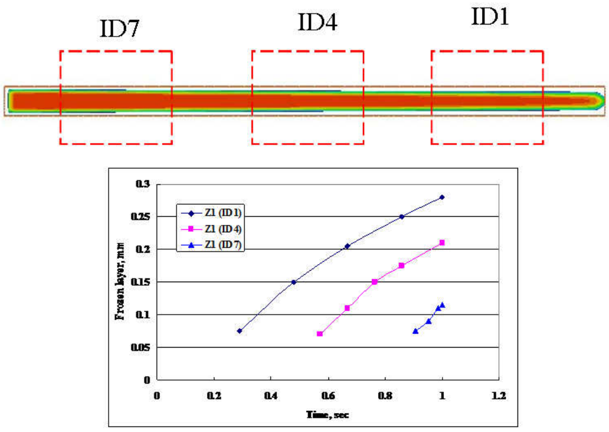


Fig. 7. The dynamic variation of frozen-layer with uniform mold temperature of 35°C in the flow direction during the filling stage.

Moreover, when the moldbase temperature is not uniform, the different cooling rate between top and bottom surfaces will influence the forming of the frozen-layer significantly. Fig. 8 shows the dynamic features of the frozen-layer developing in ID2 region for both top layer and bottom layer, where top-half of mold is 35°C; and the bottom-half is 100°C. Obviously, since the cooling rate is slower at top than that at bottom, the frozen-layer growing at top layer (Z1) is faster than that of bottom layer (Z2), from filling to packing. Hence, the central line of melt flow will be moved toward the bottom mold, and it will further affect the shear filed in this system. The dynamic variations of frozen-layer can be further observed in the perpendicular direction as shown in Fig. 9. Since the top surface contacted colder mold, the growing of the frozen-layer at top is faster than that of bottom. Hence, Z1 is lager than Z2 in all regions, from ID1 to ID3 in the perpendicular direction. Also, since ID1 and ID3 are symmetry, they have the same dynamic features. To consider the dynamic feature of frozen-layer in the flow direction, it is shown in Fig. 10. Due to the filling is performed sequentially in flow direction, the ID1 region will be frozen faster than ID4 and ID7 regions during injection molding for both top layer (Z1) and bottom layer (Z2). Even top and bottom mold temperatures are different, in all regions in the flow direction, from ID1 to ID7, it shows the similar tendency of frozen-layer growing.

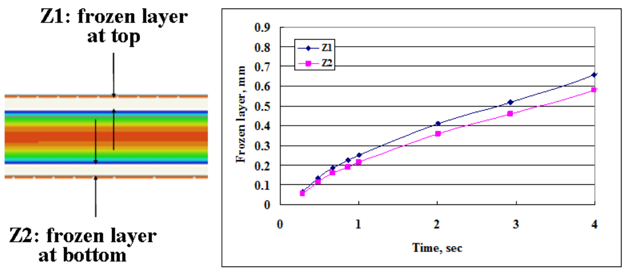


Fig. 8. The dynamic variation of frozen-layer in ID2 region with non-uniform mold temperature, where top mold is 35 °C, and bottom mold is 100 °C.

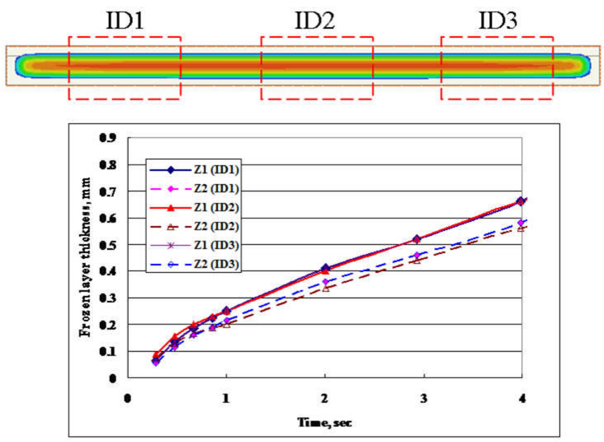


Fig. 9. The dynamic variation of the frozen-layer in the perpendicular direction with non-uniform mold temperature, where top mold is 35 °C, and bottom mold is 100 °C.

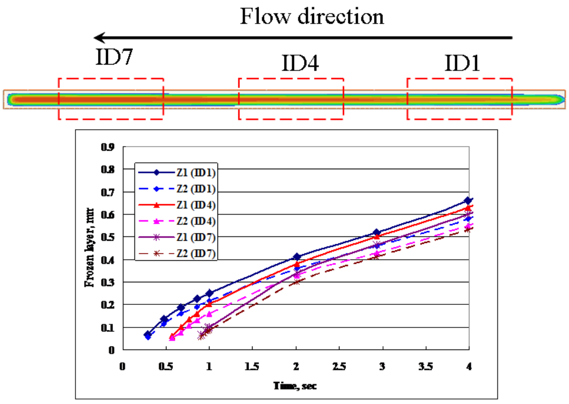


Fig. 10. The dynamic variation of the frozen-layer in the flow direction with non-uniform mold temperature, where top mold is 35 °C, and bottom mold is 100 °C

Furthermore, the relationship between the warpage and frozen-layer is also conducted. Fig. 11 shows the warpage feature at various mold temperature settings. Fig. 11(a) shows that warpage is not significant with uniform mold temperature of 35 °C. However, when the mold temperature difference between top-half and bottom-half is increased, the magnitude of warpage is varied significantly as shown in Fig. 11 (b) to (d). To catch the mechanism, we have focused on the growth of frozen-layer as shown in Fig. 12, where DZ is the difference of the frozen-layer between the top layer and bottom layer. Clearly, when the temperature of bottom mold is increased, the cooling rate of this side is slower; hence, the variation of DZ is increasing. Basically, the major contribution for warpage might be from thermal residual stresses that is supposed to come from the unbalanced frozen-layer developing which will cause the uneven shrinkage from top to the bottom. This trend is illustrated in Fig. 13, where lower mold temperature difference between top and bottom mold surfaces provides smaller trendency. Other parameters, such as shear rate variation and relaxation time, and experimental observation will be performed in the future.

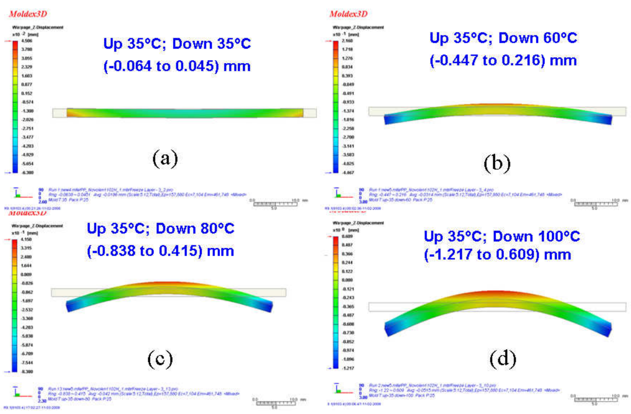


Fig. 11. Warpage behavior with non-uniform mold temperature: (a) top and bottom molds are 35 °C; (b) top mold is 35 °C, and bottom mold is 60 °C; (c) top mold is 35 °C, and bottom mold is 80 °C; (d) top mold is 35 °C, and bottom mold is 100 °C.

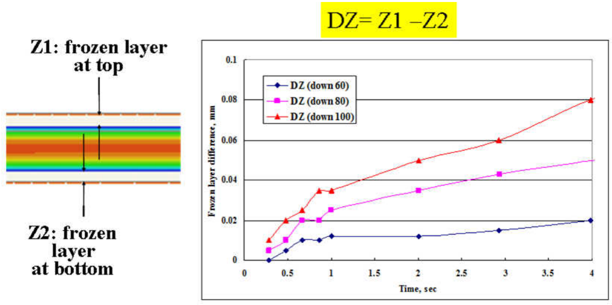


Fig. 12. The dynamic variation of the frozen-layer in ID1 with various non-uniform mold temperatures, where (down 60) means top mold is 35 °C and bottom mold is 60 °C; (down 80) means top mold is 35 °C and bottom mold is 80 °C; (down 100) means top mold is 35 °C and bottom mold is 100 °C.

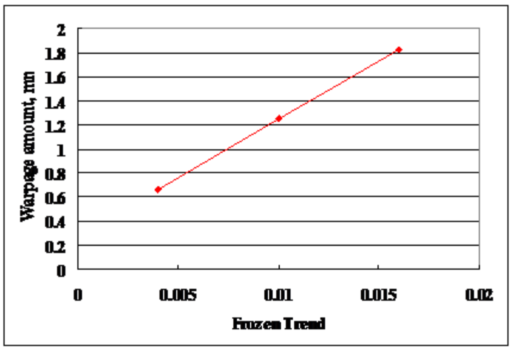


Fig. 13. The relationship between warpage and the frozen trend, where trend is the slopes of the curves in Fig. 12.

Conclusion

In this study, the dynamic features of frozen-layer formation have been investigated. Through this visualization, we have connected the frozen-layer growing mechanism to the warpage. During the injection processing, the operation conditions and the local thermal environments will influence the frozen-layer developing. Because of the unbalanced frozen-layer developing with the combination of various parameters, it will cause the uneven shrinkage from top to the bottom. It then further contributes the residual stress generation and warpage.

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Key Words: Frozen-layer, Warpage, Dynamic property, Injection molding.